

CLUSTERING IN THE LAS CAMPANAS DISTANT CLUSTER SURVEY

Anthony H. Gonzalez ¹, Dennis Zaritsky ², and Risa H. Wechsler ³¹*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138*²*Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721*³*Department of Physics, University of California, Santa Cruz, CA 95064*

Abstract. We utilize a sample of galaxy clusters at $0.35 < z < 0.6$ drawn from the Las Campanas Distant Cluster Survey (LCDCS) to provide the first non-local constraint on the cluster-cluster spatial correlation function. The LCDCS catalog, which covers an effective area of 69 square degrees, contains over 1000 cluster candidates. Estimates of the redshift and velocity dispersion exist for all candidates, which enables construction of statistically completed, volume-limited subsamples. In this analysis we measure the angular correlation function for four such subsamples at $z \sim 0.5$. After correcting for contamination, we then derive spatial correlation lengths via Limber inversion. We find that the resulting correlation lengths depend upon mass, as parameterized by the mean cluster separation, in a manner that is consistent with both local observations and CDM predictions for the clustering strength at $z=0.5$.

1 Introduction

The spatial correlation function of galaxy clusters provides an important cosmological test, as both the amplitude of the correlation function and its dependence upon mean intercluster separation are determined by the underlying cosmological model. In hierarchical models of structure formation, the spatial correlation length, r_0 , is predicted to be an increasing function of cluster mass, with the precise value of r_0 and its mass dependence determined by σ_8 (or equivalently Ω_0 , using the constraint on $\sigma_8 - \Omega_0$ from the local cluster mass function) and the shape parameter Γ . Low density and low Γ models generally predict stronger clustering for a given mass and a greater dependence of the correlation length upon cluster mass.

In this paper we utilize the Las Campanas Distant Cluster Survey (LCDCS) to provide a new, independent measurement of the dependence of the cluster correlation length upon the mean intercluster separation ($d_c \equiv n^{1/3}$) at mean separations comparable to existing Abell and APM studies. We first measure the angular correlation function for a series of subsamples at $z \sim 0.5$ and then derive the corresponding r_0 values via the cosmological Limber inversion [6, 10, 16]. The resulting values constitute the first measurements of the spatial correlation length for clusters at $z \gtrsim 0.2$. Popular structure formation models predict only a small amount of evolution from $z = 0.5$ to the present - a prediction that we test by comparison of our results with local observations.

2 The Survey

The recently completed Las Campanas Distant Cluster Survey is the largest published catalog of galaxy clusters at $z \gtrsim 0.3$, containing 1073 candidates [8]. Clusters are detected in the LCDCS as regions of excess surface brightness relative to the mean sky level, a technique that permits wide-area coverage with a minimal investment of telescope time. The final statistical catalog covers an effective area of 69 square degrees within a $78^\circ \times 1.6^\circ$ strip of the southern sky ($860 \times 24.5 h^{-1}$ Mpc at $z=0.5$ for $\Omega_0=0.3$ Λ CDM). Gonzalez et al. (2001a) also provide estimated redshifts (z_{est}), based upon the brightest cluster galaxy (BCG) magnitude-redshift relation, that are accurate to $\sim 15\%$ at $z_{est} = 0.5$, and demonstrate the existence of a correlation between the peak surface brightness, Σ , and velocity dispersion, σ . Together these two properties enable construction of well-defined subsamples that can be compared directly with simulations and observations of the local universe.

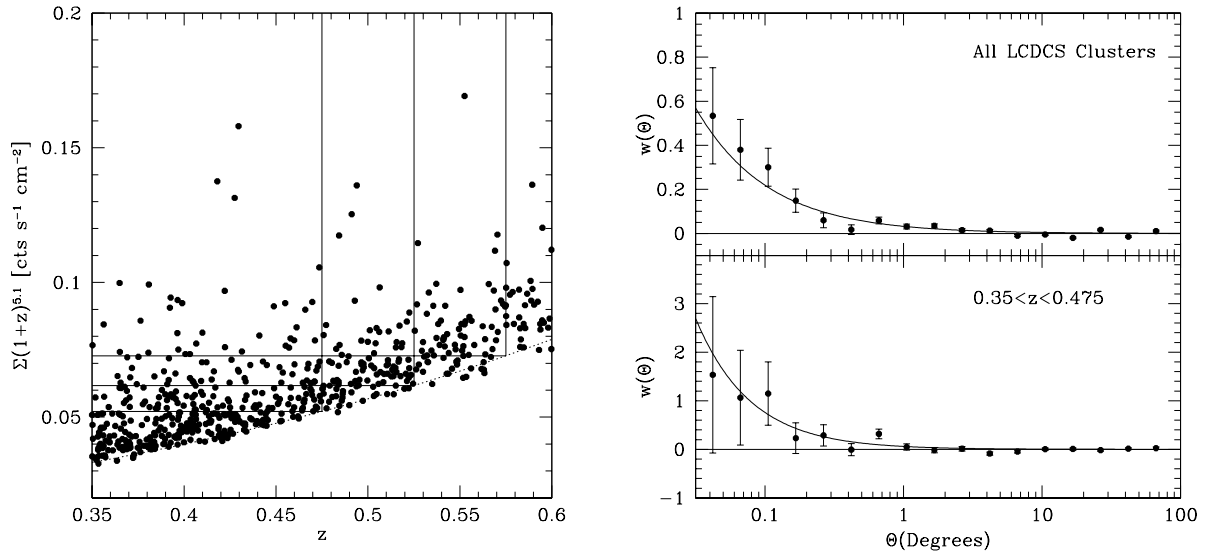


Figure 1: a/ Extinction-corrected surface brightness distribution of the LCDCS clusters used to construct subsamples. Gonzalez et al (2000a) found that $\log \sigma \propto \log \Sigma(1+z)^{5.1}$, and so we employ this relation to define subsamples that are approximately dispersion-limited. The solid lines denote the redshift and $\Sigma(1+z)^{5.1}$ thresholds of the subsamples. The dotted curve is the surface brightness threshold of the full LCDCS catalog for $E(B-V)=0.05$. Errors in the estimated redshifts move individual data points along tracks similar to this curve; b/ Angular correlation functions for the entire LCDCS catalog and for a volume-limited subsample with $0.35 \leq z < 0.475$. The solid lines are best-fit power law models.

2.1 The LCDCS Angular Correlation Function

To compute the two-point angular correlation function, we use the estimator of Landy & Szalay (1993). We measure the angular correlation function both for the full LCDCS catalog and for three approximately velocity dispersion-limited subsamples at $z \sim 0.5$ (Figure 1a). We restrict all subsamples to $z_{est} > 0.35$ to avoid incompleteness, while the maximum redshift is determined by the surface brightness threshold of the subsample.

The angular correlation function for the entire LCDCS catalog is shown in the upper panel of Figure 1b, with logarithmic angular bins of width $\delta \log \theta = 0.2$. Modeling this correlation function as a power law, $\omega(\theta) = A_\omega \theta^{1-\gamma} = (\theta/\theta_0)^{1-\gamma}$, a least-squares fit for all LCDCS clusters over the range $2'-5^\circ$ yields $\gamma = 1.83 \pm 0.12$ and $\theta_0 = 56 \pm 22''$. The angular correlation function for the lowest redshift subsample is shown in the lower panel of Figure 1b, overlaid with a best-fit power law. We derive best-fit values both allowing γ to vary as a free parameter and also fixing $\gamma = 2.1$ — equivalent to the best-fit value for the lowest redshift subsample and the best fit value for the ROSAT All-Sky Survey 1 Bright Sample [13].

We then apply a correction to these best-fit values to account for the impact of false detections in the LCDCS catalog, which for this data set act to suppress the amplitude of the observed correlation function. If we assume that the contamination is spatially correlated and can be described by a power law with the same slope as the cluster angular correlation function (a reasonable approximation because for galaxies — which are likely the primary contaminant — $\gamma \sim 1.8-1.9$ [e.g. 2, 19]), then the observed value of A_ω is

$$A_\omega = A_{\text{cluster}}(1-f)^2 + A_{\text{false}}f^2, \quad (1)$$

where f is the fractional contamination. For detections induced by isolated galaxies of the same magnitude as BCG's at $z \sim 0.35$ (and identified as galaxies by the automated identification criteria described in Gonzalez et al. (2001a)), we measure that A_{gal} is comparable to A_{ω_A} , the net clustering amplitude for all LCDCS candidates at $0.3 < z_{est} < 0.8$. For detections identified as low surface brightness galaxies (including some nearby dwarf galaxies) we measure $A_{\text{LSB}} \sim 10A_{\omega_A}$. While these systems are strongly clustered, we expect that they comprise less than half of the contamination in the LCDCS. For multiple sources of contamination the effective clustering amplitude $A_{\text{false}} = \sum A_i f_i^2 / (\sum f_i)^2$, so

Table 1: Spatial Correlation Lengths

z range	Λ CDM ($\Omega_0 = 0.3$)		OCDM ($\Omega_0 = 0.3$)		τ CDM ($\Gamma=0.2$)	
	d_c	r_0	d_c	r_0	d_c	r_0
0.35-0.475	38.4	$15.1^{+2.0}_{-2.5}$	33.8	$13.2^{+1.8}_{-2.2}$	30.9	$12.1^{+1.6}_{-2.0}$
0.35-0.525	46.3	$18.5^{+2.6}_{-3.3}$	40.6	$16.1^{+2.3}_{-2.9}$	36.9	$14.7^{+2.0}_{-2.7}$
0.35-0.575	58.1	$22.1^{+4.0}_{-5.0}$	50.8	$19.1^{+3.4}_{-4.3}$	46.0	$17.3^{+3.0}_{-4.0}$

Note — Units of r_0 and d_c are h^{-1} Mpc.

the effective clustering strength of the contamination is $A_{\text{false}} \lesssim 2.5A_{\omega_A}$ even including the LSB's.

3 The Spatial Correlation Length

The observed angular correlation function can be used to determine the three-space correlation length if the redshift distribution of the sample is known. This is accomplished via the cosmological Limber inversion [6, 10, 16]. For a power-law correlation function with redshift dependence $f(z)$,

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma} \times f(z). \quad (2)$$

The corresponding comoving spatial correlation length is $r_0(z) = r_0 f(z)^{1/\gamma}$, and the Limber equation is

$$r_o^\gamma = A_\omega \frac{c}{H_0} \frac{\Gamma(\gamma/2)}{\Gamma(1/2)\Gamma[(\gamma-1)/2]} \left[\frac{\int_{z_1}^{z_2} (dN/dz)^2 E(z) D_A(z)^{1-\gamma} f(z) (1+z) dz}{\left(\int_{z_1}^{z_2} (dN/dz) dz \right)^2} \right]^{-1}, \quad (3)$$

where dN/dz is the redshift distribution of the sample, $D_A(z, \Omega_0, \Omega_\Lambda)$ is the angular diameter distance, and $E(z)$ is defined as in Peebles (1993). Because little evolution in the clustering is expected over the redshift intervals spanned by our subsamples (see Figure 2), $f(z)$ can be pulled out of the integral.

For the LCDCS we estimate the true redshift distributions of our subsamples based upon the observed distribution of estimated redshifts. If we approximate the redshift error distribution as Gaussian with $\sigma_z/z \approx 0.14$ at $z=0.5$ [8], then the actual redshift distribution dN/dz is approximately equal to the observed redshift distribution dN_{obs}/dz for a given subsample convolved with this Gaussian scatter. To test the validity of this approach, we also try modeling dN/dz using the theoretical mass function of Sheth & Tormen (1999) convolved with redshift uncertainty. Comparing these two methods we find that the derived spatial correlation lengths agree to better than 3% for all subsamples.¹

4 Results and Comparison with Local Data

Table 3 lists the correlation lengths (r_0) and mean intercluster separations (d_c) that we derive for the three LCDCS subsamples. The values of r_0 and d_c are cosmology-dependent, so we list these quantities for three different cosmologies — Λ CDM ($\Omega_0=0.3, \Gamma=0.2$), OCDM ($\Omega_0=0.3, \Gamma=0.2$), and τ CDM ($\Gamma=0.2$). We opt to fix $\gamma=2.1$ when deriving the correlation lengths in Table 3 because γ is strongly covariant with A_ω and hence poorly constrained by the LCDCS data set. In no instance does this choice alter the derived r_0 value by more than 10% from the value obtained when γ is treated as a free parameter, but we caution that it can systematically bias the observed dependence of r_0 upon d_c . For subsamples with best-fit values of $\gamma > 2.1$, fixing gamma slightly increases the derived value of r_0 , which results in a mild steepening of the dependence of r_0 upon d_c for the LCDCS subsamples.

¹This result is insensitive to the exact mass threshold assumed for the theoretical mass function.

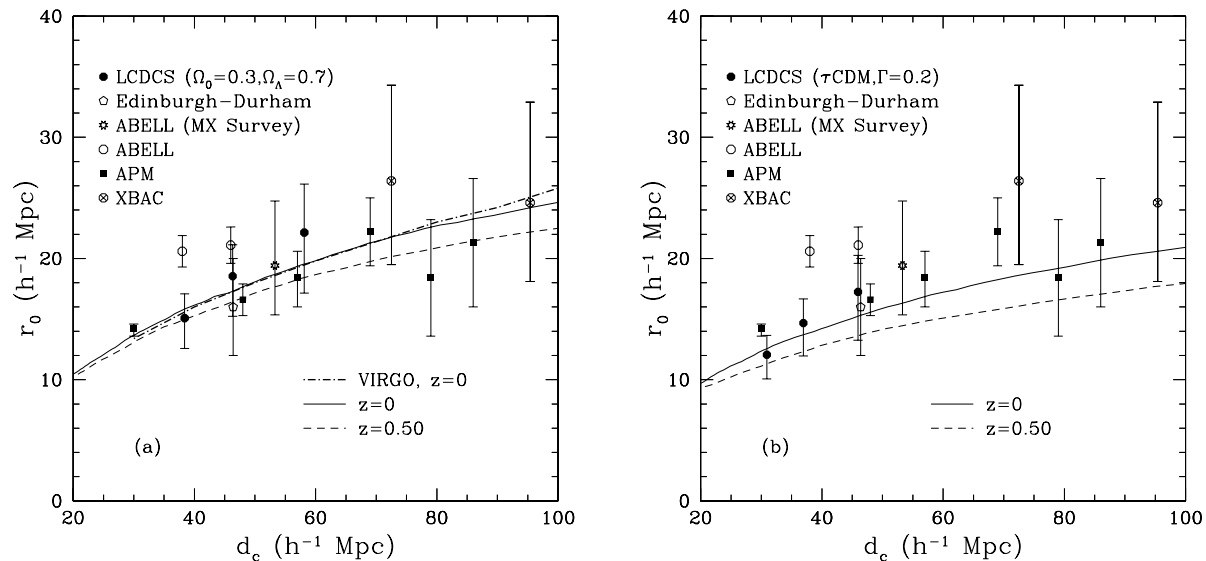


Figure 2: a/ Comparison of the LCDCS data with local samples and theoretical predictions for Λ CDM ($\Omega=0.3$). The error bars on the LCDCS data correspond to the $1-\sigma$ statistical uncertainty. Overlaid lines correspond to analytic predictions ($\Gamma=0.2$) for $z=0$ and $z=0.5$, and to results from the Virgo Consortium Hubble Volume simulations; b/ Same plot for τ CDM.

The cluster correlation function is predicted to not evolve significantly between $z=0.5$ and the present; we thus compare the LCDCS results directly with local observations, as is shown in Figure 2 for Λ CDM and τ CDM. For both cosmologies the LCDCS values of r_0 are comparable to those from the Edinburgh-Durham Galaxy Catalogue [14], APM survey [4], and the MX Survey northern sample [12], but smaller than those found by Peacock & West (1992) for the Abell catalog. Also shown are the lowest d_c data points for the XBAC catalog [1], which probe higher masses than our study.

We also plot theoretical predictions for comparison with the observational data. Results from the Virgo Consortium Hubble Volume simulations are shown as a dot-dash line in Figure 2a [3]. The other lines are analytic predictions based upon the work of Sheth & Tormen (1999). Like the APM data, the LCDCS results are consistent with the low-density models (independent of Ω_Λ). In contrast, the plotted τ CDM model systematically underestimates both the local and $z=0.5$ data. τ CDM can be made to match the data only by decreasing Γ to values that are inconsistent with constraints from the galaxy power spectrum [7].

To assess the robustness of these results, we also quantify potential systematic biases (see Gonzalez et al. 2001b for more detail). We find that our results can only be significantly altered if the uncertainty in the estimated redshifts is underestimated. If so, then the correlation lengths we derive would be systematically too small (by $\sim 2 h^{-1}$ Mpc if $\sigma_z/z=0.25$, for example). The second most significant potential systematic arises from fixing γ , which as mentioned above may lead us to overestimate the dependence of r_0 upon d_c . Treating γ as a free parameter would reduce the derived r_0 values for the three subsamples (in order of increasing d_c) by 0%, 7%, and 10%, but would not qualitatively change our results.

5 Discussion and Conclusions

The Las Campanas Distant Cluster Survey is the largest existing catalog of clusters at $z>0.3$, providing a unique sample with which to study the properties of the cluster population. We use the LCDCS to constrain the cluster-cluster angular correlation function, providing the first measurements for a sample with a mean redshift $z \gtrsim 0.2$. From the observed angular correlation function, we derive the spatial correlation length, r_0 , as a function of mean separation, d_c . Only modest evolution in the clustering amplitude is predicted between $z = 0.5$ and present, and we thus compare our results directly with local data. We find that the LCDCS correlation lengths agree with results from local samples, and observe a dependence of r_0 upon d_c that is comparable to the results of Croft et al.

(1997) for the APM catalog. This clustering strength, its dependence on number density, and its minimal redshift evolution are consistent with analytic expectations for low density models, and with results from the Λ CDM Hubble Volume simulations. Consequently, while statistical uncertainty limits our ability to discriminate between cosmological models, our results are in concordance with the flat Λ CDM model favored by recent supernovae and cosmic microwave background observations [5, 18, 20].

A final result of this analysis is that it demonstrates the utility of large catalogs like the LCDCS that are statistical in nature. While the properties of any particular cluster in the LCDCS catalog are rather uncertain, the properties of the sample as a whole are well-defined, which is sufficient for constraining properties such as the clustering strength and evolution in the comoving number density. This statistical approach requires a relatively small investment in telescope time, and so can be extended in the future to much larger samples than the LCDCS.

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